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Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector

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Abstract

This article presents an in-depth analysis of cost-effective energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel industry. We show that physical energy intensity for iron and steelmaking (at the aggregate level, standard Industrial Classification 331, 332) dropped 27%, from 35.6 GJ/tonne to 25.9 GJ/tonne between 1958 and 1994, while carbon dioxide intensity (carbon dioxide emissions expressed in tonnes of carbon per tonne of steel) dropped 39%. We provide a baseline for 1994 energy use and carbon dioxide emissions from US blast furnaces and steel mills (SIC 3312) disaggregated by the processes used in steelmaking. Energy-efficient practices and technologies are identified and analyzed for each of these processes. Examination of 47 specific energy efficiency technologies and measures found a total cost-effective reduction potential of 3.8 GJ/t, having a payback period of three years or less. This is equivalent to a potential energy efficiency improvement of 18% of 1994 US iron and steel energy use and is roughly equivalent to 19% reduction of 1994 US iron and steel carbon dioxide emissions. The measures have been ranked in a bottom-up energy conservation supply-curve.

1. Introduction

The manufacturing sector consumed 23 EJ of primary energy in the United States in 1994, almost one-quarter of all energy consumed that year [1]. Within manufacturing, a subset of raw materials transformation industries (primary metals, pulp and paper, cement, chemicals, petroleum refining) require significantly more energy than other manufacturing industries.

This article presents an in-depth analysis of one of these energy-intensive industries — iron

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and steel — identifying energy savings and carbon dioxide emissions reduction potentials. We discuss long-term historic trends in energy use and carbon dioxide emissions from the US iron and steel industry. When reviewing overall industry trends, we discuss this industry at the aggregate level (Standard Industrial Classification 331 and 332), which includes blast furnaces and steel mills (SIC 3312), electrometallurgical products (e.g. ferroalloys) (SIC 3313) and gray and ductile iron foundries (SIC 3321). The assessment of current energy use and future energy efficiency opportunities is based on a smaller portion of the industry, i.e. blast furnaces and steel mills (SIC 3312). This analysis starts with a detailed assessment of energy use on the process level to establish an energy balance of the U.S. iron and steel industry. The detailed analysis of energy-efficient practices and technologies determines specific energy savings, investment costs and changes in production costs. This assessment includes an effort to quantify so-called "non-energy benefits", e.g. productivity increases or production cost decreases as a result of implementing the new technology. The potentials for energy efficiency improvement and carbon dioxide emission reduction are assessed using a supply curve, the first detailed bottom-up energy conservation supply curve for a US industry. We end with conclusions, and suggestions to improve the analysis further.

2. Methodology

We analyze the potential for efficiency of the steel production processes in the US iron and steel industry, i.e. blast furnaces and steel mills (SIC 3312). The analysis consists of three steps. First, we establish a 1994 baseline for energy and material use, using data from the last year for which detailed national energy statistics are available [1]. The second step is the analysis and characterization of energy-efficient technologies to improve energy efficiency, and determine the potential application and impact of these measures. Finally, we assess the cost-effectiveness of the potential for energy efficiency improvement, using a so-called energy conservation supply curve.

Throughout this paper, primary energy is calculated using a conversion rate from final to primary electricity of 3.08 (equivalent to a power generation efficiency of 32.5%) excluding transmission & distribution losses. Energy is expressed in higher heating value (HHV), as is common in US energy statistics. Carbon dioxide emissions are expressed in metric tons carbon. The carbon conversion factors used for calculating carbon emissions from energy consumption are taken from the Energy Information Administration [2]. In the historic trend analysis, electricity conversion factors vary annually based on the fuel mix used for power generation. Steel contains less than 1.7% carbon. We have not subtracted the embodied carbon in the primary steel production by OHF and BOF. Production is expressed in metric tons. Hence, we define energy intensity in terms of physical output rather than economic output. Worrell et al. [3] demonstrated that economic indicators of energy intensity do not always accurately reflect physical trends and concluded that physical energy intensity measurements should be used when possible.

2.1. Establishing a baseline for energy use in the US iron and steel industry

Energy use for each of the processes has been subdivided to the major processes used in the steel industry. The main energy-using processes for integrated steel production are sintermaking, cokemaking, ironmaking, steelmaking. Pelletizing, the production of iron ore pellets, is normally undertaken at the mining site and is not included in our analysis. Only the steelmaking step is used for production of secondary steel.[1] Following steel production, energy is used for casting, hot rolling, cold rolling, and finishing. Energy consumption data (see Table 2) are based on data from the American Iron and Steel Association's *Annual Statistical Report* [4] and *Manufacturing Energy Consumption Survey* [1]. When data on specific sub-processes were not available, consumption estimates were based on process energy intensity estimates and throughput from available literature (e.g. [5]). Oxygen production is not included in the energy use estimates, as this is often outsourced by steel industries. Emissions from limestone use as fluxing agent in iron- and steelmaking are not included in the CO_2 emission estimates.

2.2. Characterization of energy efficient technologies

To analyze the potential for reducing energy use and carbon dioxide emissions from steelmaking in the US, we compiled information on the costs, energy savings, and carbon dioxide emissions reductions of a number of technologies and measures. The technologies and measures fall into two categories: commercially available measures that are currently in use in steel mills worldwide and advanced measures that are either only in limited use or are near commercialization. We focus on retrofit measures using commercially available technologies, but many of these technologies are applicable for new plants as well. For each technology or measure, we estimate costs and energy savings per tonne of crude steel produced in 1994. We then calculate carbon dioxide emissions reductions based on the fuels used at the process step to which the technology or measure is applied. Fuel and electricity savings for each efficiency measure in Tables 4 and 5 were usually calculated as savings per tonne product (e.g. 0.5 GJ/t sinter). To convert savings from a per tonne product basis to a per tonne crude steel basis we multiplied the savings by the ratio of throughput (production from a specific process) to total crude steel. For example, if a measure saves 1 GJ/t *pig iron*, the equivalent savings per tonne of primary *crude steel* would equal 0.89 GJ/t crude steel (1*49.4 Mt pig iron production/55.4 Mt integrated crude steel production). Operating and capital costs are also calculated on a crude steel basis according to the same methodology as fuel and electricity savings. Our determination of the share of production to which each measure is applied was based on a variety of information sources on the U.S. iron and steel industry in 1994 and expert judgment [6].

Finally, carbon dioxide emissions reductions for each measure were calculated based on a weighted average carbon dioxide emissions coefficient (*tC/GJ*) for each process step. We have attempted to account for interactive effects of competing measures, or reduced effectiveness of measures due to previous implementation of a measure. This is done by limiting the penetration rate of competing measures, and by assuming an order of implementation of the measures, which reduce the potential savings of subsequent measures after implementation of measure affecting other measures. We generally assumed that the most cost-effective technology was implemented first, unless technical reasons determine the order of implementation.

[1] Secondary steel is produced from scrap and/or direct reduced iron (DRI, also called sponge iron). While DRI production is growing, it comprised only 2% of secondary steel inputs in 1994 [4].

2.3. Energy conservation supply curves

Supply curves are a common tool in economics. In the 1970s energy conservation supply curves were developed by energy analysts as a means of ranking energy conservation investments alongside investments in energy supply in order to assess the least cost approach to meeting energy service needs [7]. Conservation supply curves rank energy efficiency measures by their "cost of conserved energy" (CCE), which accounts for both the costs associated with implementing and maintaining a particular technology or measure and the energy savings associated with that option over its lifetime. The CCE of a particular option is calculated following Eq. (1)

$$\mathrm{CCE}=\frac{\text{Annualized Investment+Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \tag{1}$$

The annualized investment is calculated following Eq. (2).

$$\text{Annualized Investment}=\text{Capital Cost}\times\frac{d}{(1-(1+d)^{-n})} \tag{2}$$

where d is the discount rate and n is the lifetime of the conservation measure. In this analysis we use a discount rate of 30% to simulate the investment criteria commonly used by industry. CCEs are calculated for each measure that can be applied in a certain sector or subsector (e.g. steelmaking) and then ranked in order of increasing CCE [8]. Once all options have been properly ranked, a conservation supply curve can be constructed. Defining "cost-effective" involves choosing a discount rate that reflects the desired perspective (e.g. customer, society). Then all measures that fall below a certain energy price, such as the average price of energy for the sector, can be defined as cost-effective.

The CCEs are plotted in ascending order to create a conservation supply curve. This curve is a snapshot of the total annualized cost of investment for all of the efficiency measures being considered at that point in time. The width of each option or measure (plotted on the x-axis) represents the annual energy saved by that option. The height (plotted on the y-axis) shows the option's CCE.

The advantage of using a conservation supply curve is that it provides a clear, easy-to-understand framework for summarizing complex information about energy efficiency technologies, their costs, and the potential for energy savings. The curve can avoid double counting of energy savings by accounting for interactions between measures, is independent of prices, and also provides a framework to compare the costs of efficiency with the costs of energy supply technologies.

This conservation supply curve approach also has certain limitations. In particular, the potential energy savings for a particular sector are dependent on the measures that are listed and/or analyzed at a particular point in time. There may be additional energy efficiency measures or technologies that do not get included in an analysis, so savings may be underestimated. The costs of efficiency improvements (initial investment costs plus operation and maintenance costs) do not include transaction costs for acquiring all the appropriate information needed to evaluate and choose an investment and there may be additional investment barriers (e.g. opportunity costs) that are not accounted for in the analysis [9,10].

Many analysts use internal rate of return (IRR) to rate the cost effectiveness of various investments, which is the value of the discount rate to make the net benefits stream equal to the initial investment. A key difference between CCE and IRR is that with an IRR the fuel price for the analysis period is included in the calculation (since energy savings are quantified on a dollar basis), and therefore has a direct effect on the evaluation of a measure. With the CCE calculation changes in fuel prices will not change the CCE of a measure but will change the number of measures that are considered cost effective.

For our analysis, we used a 30% real discount rate, reflecting the steel industry's capital constraints and preference for short payback periods and high internal rates of return. We use an industry average weighted fuel cost in our calculation based on energy data provided by the American Iron and Steel Institute, and cost data from EIA [1]. We include a weighted fuel cost separate for integrated or for secondary steel making and we use the source price of electricity.

Many energy efficiency measures provide economic and environmental benefits in addition to energy and energy cost savings. Economic benefits may include improved productivity, reduced raw materials costs, or reduced operation costs (e.g. reduced electrode use in EAFs). Environmental benefits may result in reduced particulate emissions (e.g. dry coke quenching replacing the wet quenching process), reduced NOx, SOx, and other criteria pollutant emissions (e.g fuel injection in the blast furnace replacing cokemaking). We have quantified the economic benefits in the analysis of the costs, to the degree possible using available data in the literature. However, productivity benefits are often determined by specific site-specific conditions, and may vary accordingly. We have not included quantified estimates of environmental benefits in the current work. This is a subject, however, that merits continued research.

3. Overview of US iron and steel industry

The US iron and steel industry is made up of *integrated steel mills* that produce pig iron from raw materials (iron ore, coke) using a blast furnace and steel using a basic oxygen furnace (BOF) and *secondary steel mills* that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using an electric arc furnace (EAF). The majority of steel produced in the US is from integrated steel mills, although the share of secondary steel mills (or "minimills") is increasing, growing from 15% of production in 1970 to 40% in 1995 [4].

There were 142 operating steel plants in the US in 1997 (see Fig. 1). At that time, there were 14 integrated steel companies operating 20 integrated steel mills with a total of 40 blast furnaces [11]. These mills are concentrated in the Great Lakes region, near supplies of coal and iron ore and near key customers such as the automobile manufacturers. The blast furnaces in these mills range in age—accounting for furnace rebuilds—from 2 to 67 years, with an average age of 29 years. Production rates per plant vary between 0.5 and 3.1 million metric tons (Mt) per year. Total production of US blast furnaces in 1997 was slightly over 54 Mt steel [12].

Secondary steel mills are located throughout the US. In 1997 there were 85 secondary steel companies operating 122 minimills with 226 EAFs. These facilities are spread throughout 35 states, with the largest number of plants in Pennsylvania, Ohio, and Texas. The electric arc furnaces at these mills range in age from 0 (just starting production in 1997) to 74 years, with an average age of 24 years. Total annual nominal capacity listed in 1994 was 50.4 Mt and the average power consumption is 480 kWh/t [12]. Between 1995 and 1997 an additional 12 Mt of electric arc furnace capacity was built.

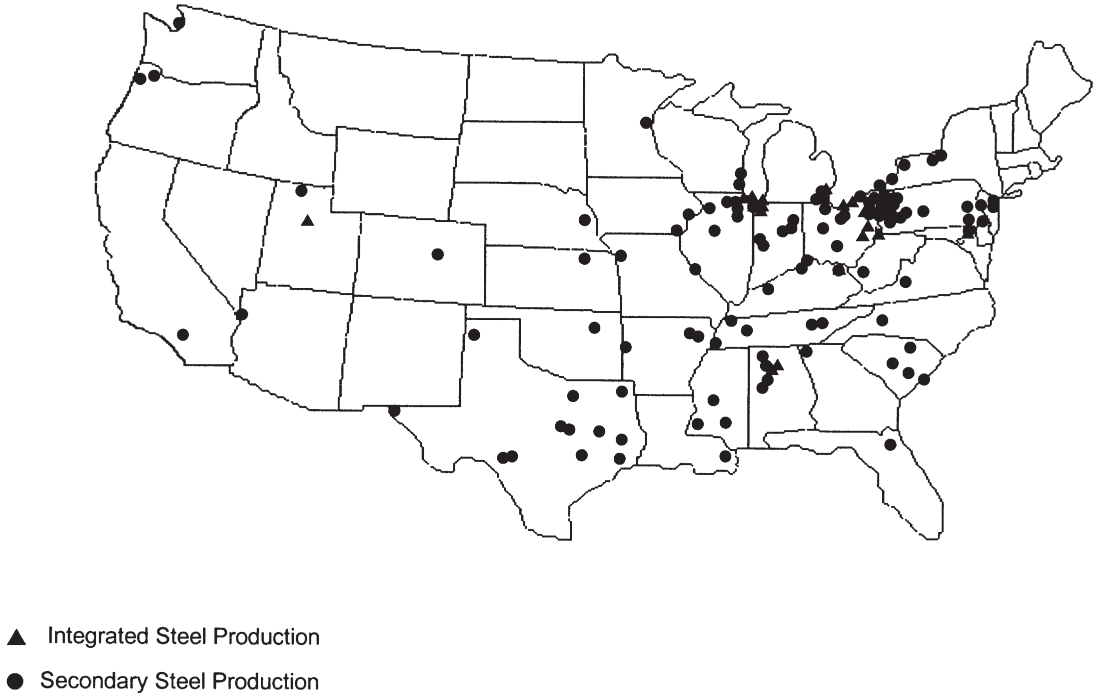

Fig. 1. Location of integrated and secondary steel mills in the US in 1997. Source: [11,12].

Fig. 2 shows that steel production in the US has fluctuated dramatically since 1970, when production was just below 120 Mt. Production peaked at 136 Mt in 1973 and fluctuated between 100 and 130 Mt until it crashed to 68 Mt in 1982 as a result of a dramatic number of integrated mill closures. Since 1982, production has grown slowly, with two major declines in 1985–86 and 1991. In 1995, production reached 95 Mt. During this period, primary steel production using inefficient open hearth furnaces dropped from 44 Mt in 1970 to 6 Mt in 1982 and was completely phased out by 1992. Primary steel production using BOF fluctuated between 40 and 10.75 Mt over the period. EAF production more than doubled, growing from 18 to 38 Mt between 1970 and 1995 [4].

4. Trends in energy use and carbon dioxide emissions in the US iron and steel industry (SIC 331, 332)

4.1. Historical energy use and carbon dioxide emissions trends

Final energy use for the iron and steel industry (SIC 331, 332) fluctuated significantly between 1958 and 1994, starting at 2.6 EJ (2.8 EJ primary energy) in 1958, climbing to 3.9 EJ (4.4 EJ primary energy) in 1973, dropping to 1.9 EJ (2.3 EJ primary energy) in 1982, and remaining level at 1.9 EJ of final energy (2.4 EJ primary energy) in 1994 (see Fig. 3). Between 1958 and 1994 the share of coal and coke used as energy sources dropped from about 75% to 57% of total

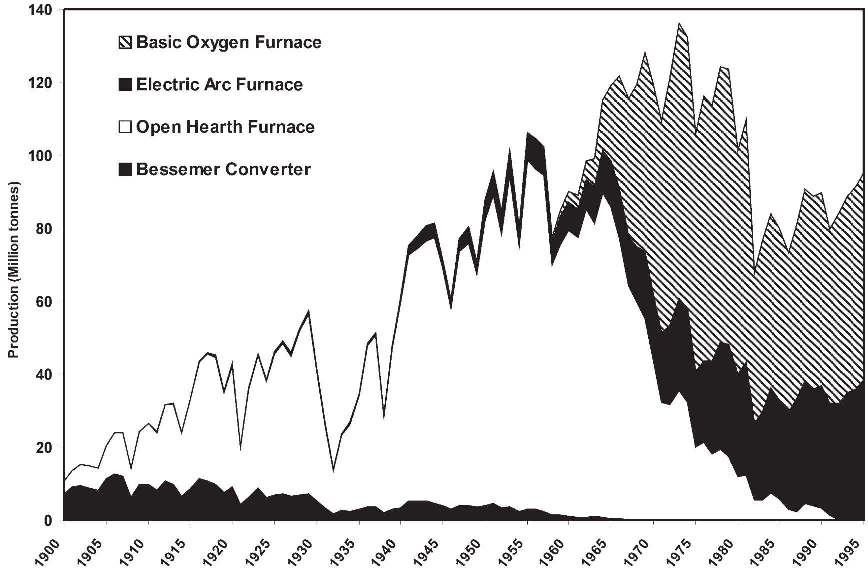

Fig. 2. US steel production by process from 1970 to 1995, expressed in Million tonnes per year. Source: AISI [4].

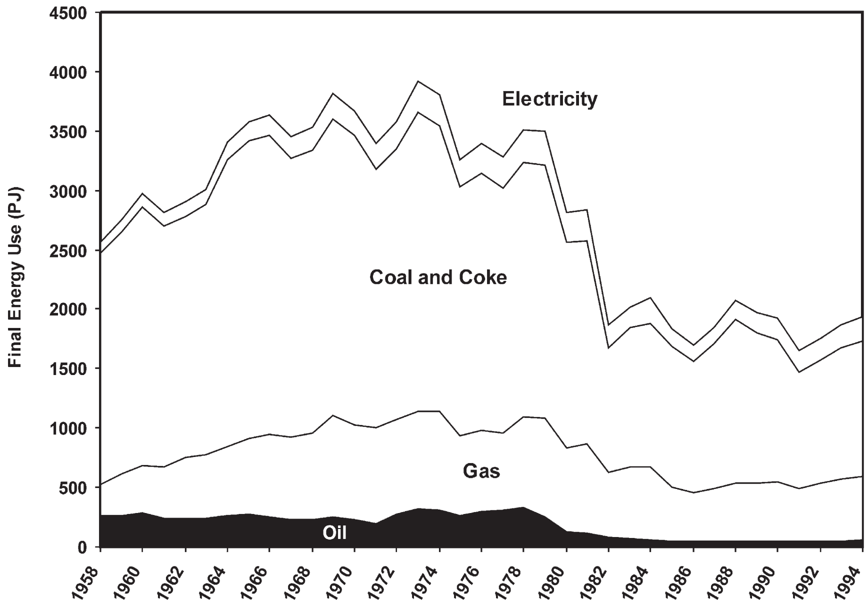

Fig. 3. Final energy use for US iron and steel production, expressed in PJ. Source: LBNL [13]. Final energy use excludes transformation losses for purchased electricity.

fuels, followed by a drop in the share of oil from 10% to 3%. The share of natural gas used in the industry increased from 10% to 28%. The share of electricity increased from 4% to 11% during the same period, in large part due to increased secondary steel production. Carbon dioxide emissions trends (expressed in million metric tonnes (MtC) of carbon) have followed energy use trends (see Fig. 4), with emissions of 64 MtC in 1958, 96 MtC in 1973, and 45 MtC in 1994 [13].

4.2. Energy and carbon dioxide intensity trends

Physical energy intensity of U.S. steel production, defined as primary energy use for SIC 331 and 332 per metric ton of steel produced, dropped 27%, from 35.6 GJ/t to 25.9 GJ/t, between 1958 and 1994.[2] Decomposition analyses indicate that about two-thirds of the decrease between 1980 and 1991 was due to efficiency improvements, while the remainder was due to structural changes, e.g. change to more cold-rolled steel production [3]. Carbon dioxide intensity dropped from 0.82 tC/t to 0.50 tC/t (excluding emissions from power generation for purchased power), during this period, reflecting the general decrease in energy use per tonne of steel produced as well as fuel switching. The most important change was the growing use of scrap-based EAFs for secondary steel production, which grew from 17% to 39% of total steel production during this period. Efficiency improvement can be explained mainly by the increased use of continuous cast-

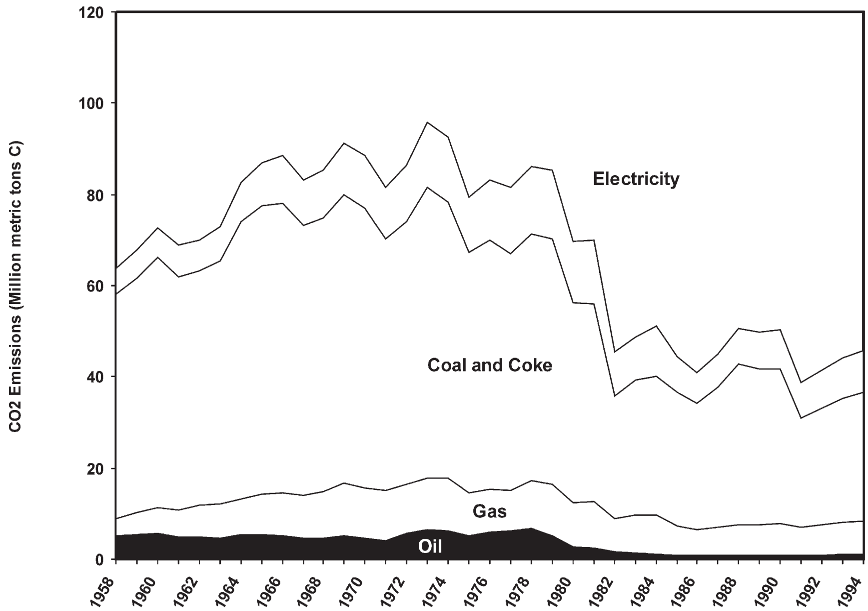

Fig. 4. Carbon dioxide emissions from energy by the US iron and steel industry, expressed in MtC. Source: LBNL [13]. The emissions exclude emissions from electricity production for purchased electricity.

[2] Energy consumption values from 1991 through 1994 include SIC 3312 (blast furnaces and steel mills) 3313 (electrometallurgical products) and 3321 (gray and ductile iron foundries) in order to better match historical aggregate data. Due to limited coverage in the US DOE, EIA *Manufacturing Energy Consumption Survey*, data for 1985 through 1990 reflect energy use for SIC 3312 only, and therefore may be roughly 5–8% lower than energy use for the more aggregate SIC 331–332.

ing, which grew from 0% in 1971 to 89% in 1994, and the closing of inefficient open hearth furnace steelmaking, which dropped from 30% in 1971 to 0% after 1991. In addition, the increased use of pellets as blast furnace feed contributed to the energy savings [3,14].

Despite these overall improvements, energy intensity of steel production in the U.S. increased slightly between 1991 and 1994, growing from 25.2 GJ/t to 25.9 GJ/t [15], reversing the long-term downward trend.[3] Based on trends in three key areas (increased share of electric arc furnaces from 38% to 39%, retirement of all remaining open hearth furnaces, and increase in the use of continuous casting from 76% in 1991 to 89% in 1994) this increase is unexpected. Trends that may have contributed to the increased energy use include a move toward more extensively treated, higher quality cold rolled steel and increased capacity utilization leading to the use of older, less-efficient integrated steel mills [5].

5. 1994 Baseline energy use and carbon dioxide emissions for energy use in US blast furnaces and steel mills (SIC 3312)

5.1. Energy use and carbon dioxide emissions by process in US steelmaking

For our detailed analysis of the US iron and steel industry, we focus on a smaller portion of the industry, blast furnaces and steel mills (SIC 3312). In 1994, integrated steel mills in the US produced 55.4 Mt of steel and secondary steel mills produced 35.87 Mt, for a total US production of 91.3 Mt. Table 1 provides an estimate of the energy use and carbon dioxide emissions from energy use by process for production of steel in the US in 1994. Primary energy use for integrated steelmaking was about three times greater than energy use in secondary steelmaking, consuming 1439 PJ compared to 425 PJ. The primary energy intensity of integrated and secondary steel production in 1994 was 26.0 GJ/t and 11.8 GJ/t, respectively, for a total sector primary energy intensity of 20.4 GJ/t. Total carbon dioxide emissions from steelmaking in 1994 were 34.4 MtC, with 80% of these emissions from integrated steelmaking. This emission estimate includes the average 1994 US carbon dioxide emissions from power generation for electricity purchased by the iron and steel industry. The carbon dioxide intensity of integrated steelmaking was 0.5 tC/t crude steel while the carbon dioxide intensity for secondary steelmaking was 0.2 tC/t crude steel, resulting in a total sector carbon dioxide intensity of 0.4 tC/t crude steel.

6. Technologies and measures to reduce energy use and carbon dioxide emissions

To analyze the potential for reducing energy use and carbon dioxide emissions from steelmaking in the US, we assessed 47 energy efficient practices and technologies (see Table 2). Below we provide a detailed description of one of these technologies, scrap preheating, as an example. Worrell et al. [6] provides a detailed analysis of all of the technologies included in the assessment.

[3] These energy intensity values are calculated using energy use data from the US *Manufacturing Energy Consumption Survey* and accounts for energy used in coke production and for coke shipments [2,16]. We note that energy use data of the American Iron and Steel Institute show an 8% decline in primary energy intensity between 1990 and 1994 [5].

Table 1
Energy use and carbon dioxide emissions by process in US steel production, 1994

Process stage	Fuel (PJ)	Electricity (PJ)	Final energy (PJ)	Primary energy (PJ)	Carbon dioxide emissions (MtC)[c]
Integrated steelmaking					
Sintermaking	26	2	28	31	0.8
Cokemaking	74	2	76	81	0.6
Ironmaking	676	4	680	689	11.0
Steelmaking (basic oxygen furnace)	19	6	25	36	0.5
Casting	15	11	27	50	0.9
Hot rolling	157	34	191	263	3.7
Cold rolling and finishing	43	15	58	89	1.3
Boilers (integrated steelmaking)	167	0	167	167	7.8
Cogeneration (integrated steelmaking)	101	−22	79	101	0.4
Total (integrated steelmaking)	1280	52	1332	1439	27.0
Secondary steelmaking					
Steelmaking (electric arc furnace)	6	62	68	197	2.8
Casting	1	4	5	12	0.2
Hot rolling	102	22	124	170	2.4
Cold rolling and finishing[a]	0	0	0	0	0.0
Boilers (secondary steelmaking)[b]	42	0	42	42	2.0
Cogeneration (secondary steelmaking)	11	−2	9	11	0.04
Total secondary steelmaking	162	85	248	425	7.4
Total primary and secondary steelmaking	1443	137	1580	1864	34.4

[a] In 1994, no EAF plants used a cold rolling mill. Since then, however, at least 3 mills are using this process.
[b] In EAF mills steam is used for the vacuum degasser and for the production of speciality steels.
[c] Carbon dioxide emissions are calculated using the guidelines for emission factors as established by the Intergovemmental Panel on Climate Change (IPCC).

Scrap preheating is a technology that can reduce the power consumption of EAFs through using the waste heat of the furnace to preheat the scrap charge. Old bucket preheating systems had various problems, such as emissions, high handling costs, and a relatively low heat recovery rate. Modern systems have reduced these problems and are highly efficient. The energy savings depend on the preheat temperature of the scrap. Various systems have been developed and are in use at sites in the US and Europe, i.e. Consteel tunnel-type preheater, Fuchs Finger Shaft, and Fuchs

Table 2
State-of-the-art energy efficiency measures in the US iron and steel industry

Overall Measures (measures apply to both integrated and secondary plants)	
Preventative maintenance	
Energy monitoring and management systems	
Variable speed drives for flue gas control, pumps, and fans	
Cogeneration	
Integrated Steel Making Measures	**Secondary Steel Making Measures**
Iron Ore Preparation (Sintermaking)	Electric Arc Furnace
Sinter plant heat recovery	Improved process control (neural networks)
Use of waste fuels in the sinter plant	Flue gas monitoring and control
Reduction of air leakage	Transformer efficiency measures
Increasing bed depth	Bottom stirring/gas injection
Improved process control	Foamy slag practices
Coke Making	Oxy-fuel burners/lancing
Coal moisture control	Post-combustion
Programmed heating	Eccentric bottom tapping (EBT)
Variable speed drive on coke oven gas compressors	Direct current (DC) arc furnaces
Coke dry quenching	Scrap preheating
Iron Making - Blast Furnace	Consteel process
Pulverized coal injection (medium and high levels)	Fuchs shaft furnace
Injection of natural gas	Twin shell DC arc furnace
Top pressure recovery turbines (wet type)	
Recovery of blast furnace gas	
Hot blast stove automation	
Recuperator on the hot blast stove	
Improved blast furnace control	
Steel making — Basic oxygen furnace	
BOF gas & sensible heat recovery (supressed combustion)	
Variable speed drive on ventilation fans	
Casting and rolling (measures apply to integrated and secondary plants unless otherwise specified)	
Casting	
Adopt continuous casting	
Efficient ladle preheating	
Thin slab casting	
Rolling	
Hot charging	
Recuperative burner in the reheating furnace	
Controlling oxygen levels and variable speed drives on combustion air fans	
Process control in the hot strip mill	
Insulation of furnaces	
Energy efficient drives in the hot rolling mill	
Waste heat recovery from cooling water	
Heat recovery on the annealing line (integrated only)	
Automated monitoring & targeting system	
Reduced steam use in the pickling line	

Twin Shaft. Twin shell furnaces can also be used as scrap preheating systems. All systems can be applied to new construction and to retrofit existing plants. The Consteel process consists of a conveyor belt with the scrap going through a tunnel, down to the EAF through a "hot heel". Besides energy savings, the Consteel process results in an productivity increase of 33%, reduced electrode consumption of 40% and reduced dust emissions [17]. The FUCHS shaft furnace consists of a vertical shaft that channels the offgases to preheat the scrap. The scrap can be fed continuously (4 plants installed worldwide) or through a so-called system of "fingers" (15 plants installed worldwide). The Fuchs systems make almost 100% scrap preheating possible, leading to potential energy savings of 100–120 kWh/ton [18]. The energy savings depend on the scrap used and the degree of post-combustion (oxygen levels). The scrap preheating systems lead to reduced electrode consumption, yield improvement of 0.25–2%, up to 20% productivity increase and 25% reduced flue gas dust emissions (reducing hazardous waste handling costs) [19]. Electricity use can be decreased to approximately 370–390 kWh/ton using the Consteel process [20], without supplementary fuel injection in retrofit situation, while consumption as low as 340–360 kWh/ton has been achieved in new plants [21]. Using post-combustion the energy consumption is estimated to be 340 to 350 kWh/t and 0.7 GJ/t fuel injection [22]. The extra investments are estimated to be $2 Million (1989$) for a capacity of 400 000 to 500 000 tonne per year. Correcting for inflation, this results in specific investments of approximately $4.4 to $6.0/t for the Consteel process. The annual cost savings are estimated to vary between $1.9/t and $4.5/t [18,23]. The simple payback period of installing a scrap preheater is estimated at 1 to 2 years for large furnaces. Various US plants have installed a Consteel process, i.e. AmeriSteel (Charlotte, NC), New Jersey Steel (Sayreville, NJ) and Nucor (Darlington, SC). The installation at New Jersey Steel is a retrofit of an existing furnace. Fuchs systems have been installed at North Star (Kingman, AZ), North Star-BHP (Delta, OH), Birmingham Steel (Memphis, TN) and Texas Industries (Richmond, VA). In addition, North Star has ordered another preheater for their Youngstown (OH) plant.

6.1. Assessment of individual practices and technologies

The results of the analysis are summarized in Tables 3 and 4. Table 3 provides total production, fuel, electricity, and primary energy savings per tonne of crude steel; annual operating costs; capital costs per tonne of crude steel; percentage of production to which the measure is applied nationally; and carbon dioxide emissions reductions for each measure applied to the production of primary steel in an integrated mill. Table 4 provides similar information for production of secondary steel. Tables 3 and 4 also present information on the non-energy benefits, as changes in annual operating costs. The large reductions of annual operating costs for some measures, e.g. hot charging, thin slab casting, fuel injection in the blast furnace, show the importance for the economic assessment of the potential for efficiency improvement. The annual operating cost reductions also influence the shape of the supply curve and hence the cost-effective potential.

Advanced technologies and measures for reducing energy use and carbon dioxide emissions include smelt reduction processes for integrated steelmaking, the Contiarc and Comelt processes for secondary steelmaking, and strip casting [24]. These technologies are not currently in commercial use (except the COREX smelt reduction process) for steel production, so we do not include them in this analysis.

Table 3
Energy savings, costs, and carbon dioxide emissions reductions for energy-efficiency technologies and measures applied to integrated steel production in the US in 1994

Option	Production (Mtonne)	Fuel savings (GJ/tonne crude steel)	Electricity savings (GJ/tonne crude steel)	Primary energy savings (GJ/tonne crude steel)	Annual operating costs (US$/tonne crude steel)	Retrofit capital cost (US$/tonne crude steel)	Carbon dioxide emissions reduction (kgC/t)	Share of production measure applied (percent)
Iron ore preparation (Sintering)								
Sinter plant heat	12.1	0.12	0.00	0.12	0.00	0.66	3.41	100%
Reduction of air leakage	12.1	0.00	0.00	0.01	0.00	0.02	0.12	100%
Increasing bed depth	12.1	0.02	0.00	0.02	0.00	0.00	0.59	100%
Improved process control	12.1	0.01	0.00	0.01	0.00	0.03	0.30	100%
Use of waste fuels in sinter plant	12.1	0.04	0.00	0.04	0.00	0.04	1.16	74%
Coke making								
Coal moisture control	16.6	0.09	0.00	0.09	0.00	14.69	0.55	100%
Programmed heating	16.6	0.05	0.00	0.05	0.00	0.07	0.31	100%
Variable speed drive coke oven gas compressors	16.6	0.00	0.00	0.00	0.00	0.09	0.01	100%
Coke dry quenching	16.6	0.37	0.00	0.37	0.15	20.99	2.25	100%
Iron Making — Blast Furnace								
Pulverized coal injection to 130 kg/thm	49.4	0.69	0.00	0.69	−1.78	6.24	11.42	80%
Pulverized coal injection to 225 kg/thm	49.4	0.51	0.00	0.51	−0.89	4.64	8.45	30%
Injection of natural gas to 140 kg/thm	49.4	0.80	0.00	0.80	−1.78	4.46	13.35	20%
Top pressure recovery turbines (wet type)	49.4	0.00	0.10	0.30	0.00	17.84	4.29	20%
Recovery of blast furnace gas	49.4	0.06	0.00	0.06	0.00	0.27	0.98	60%
Hot blast stove automation	49.4	0.33	0.00	0.33	0.00	0.27	5.49	60%
Recuperator hot blast stove	49.4	0.07	0.00	0.07	0.00	1.25	1.19	100%
Improved blast control systems	49.4	0.36	0.00	0.36	0.00	0.32	5.93	50%

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Table 3 (*continued*)

Option	Production (Mtonne)	Fuel savings (GJ/tonne crude steel)	Electricity savings (GJ/tonne crude steel)	Primary energy savings (GJ/tonne crude steel)	Annual operating costs (US$/tonne crude steel)	Retrofit capital cost (US$/tonne crude steel)	Carbon dioxide emissions reduction (kgC/t)	Share of production measure applied (percent)
Steelmaking — Basic Oxygen Furnace								
BOF gas+sensible heat recovery	55.4	0.92	0.00	0.92	0.00	22.00	12.55	100%
Variable speed drive on ventilation fans	55.4	0.00	0.00	0.01	0.00	0.20	0.14	100%
Integrated Casting								
Adopt continuous casting	49.5	0.24	0.08	0.49	−5.35	11.95	36.06	9%
Efficient ladle preheating	49.5	0.02	0.00	0.02	0.00	0.05	0.27	84%
Thin slab casting	49.5	3.13	0.57	4.89	−31.33	134.25	177.60	20%
Integrated Hot Rolling								
Hot charging	48.3	0.52	0.00	0.52	−1.15	13.09	7.18	22%
Process control in hot strip mill	48.3	0.26	0.00	0.26	0.00	0.61	3.59	69%
Recuperative burners	48.3	0.61	0.00	0.61	0.00	2.18	8.38	20%
Insulation of furnaces	48.3	0.14	0.00	0.14	0.00	8.73	1.91	30%
Controlling oxygen levels and VSDs on combustion air fans	48.3	0.29	0.00	0.29	0.00	0.44	3.95	50%
Energy efficient drives (rolling mill)	48.3	0.00	0.01	0.03	0.00	0.17	0.39	50%
Waste heat recovery (cooling water)	48.3	0.03	0.00	0.03	0.06	0.70	0.46	69%
Integrated Cold Rolling and Finishing								
Heat recovery on the annealing line	31.7	0.17	0.01	0.19	0.00	1.55	2.73	50%
Reduced steam use (pickling line)	31.7	0.11	0.00	0.11	0.00	1.61	1.55	80%
Automated monitoring and targeting system	31.7	0.00	0.12	0.38	0.00	0.63	5.51	50%
General								
Preventative maintenance	55.4	0.43	0.02	0.49	0.02	0.01	9.74	100%

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Table 3 (*continued*)

Option	Production (Mtonne)	Fuel savings (GJ/tonne crude steel)	Electricity savings (GJ/tonne crude steel)	Primary energy savings (GJ/tonne crude steel)	Annual operating costs (US$/tonne crude steel)	Retrofit capital cost (US$/tonne crude steel)	Carbon dioxide emissions reduction (kgC/t)	Share of production measure applied (percent)
Energy monitoring and management system	55.4	0.11	0.01	0.14	0.00	0.15	2.60	100%
Cogeneration	55.4	0.03	0.35	1.1	0.00	14.52	22.39	100%
Variable speed drive, flue gas control, pumps, fans	55.4	0.00	0.02	0.06	0.00	1.30	0.40	50%

7. Potential for energy efficiency improvement and carbon dioxide emissions reduction

7.1. Energy conservation supply curve for US integrated steelmaking

We identified cost-effective energy savings of 236 PJ and carbon dioxide emissions reductions of 5.0 MtC for integrated steelmaking in 1994 which represents 13% of total US steelmaking energy use and 15% of total carbon dioxide emissions. Fig. 5 ranks the integrated steelmaking measures in a conservation supply curve; the cost-effective measures are those which fall below the average weighted energy supply cost for 1994, and are therefore cost effective at 1994 energy prices using a discount rate of 30%. Some of the largest cost-effective energy savings appear possible with such measures as preventative maintenance, coal injection into the blast furnace, and improvements in monitoring and control systems for the blast furnace and rolling mills. Table 5 provides a list of the measures ranked by their cost of conserved energy, internal rate of return, and their simple payback periods.

7.2. Energy conservation supply curve for US secondary steelmaking

We identified cost-effective energy savings of 104 PJ and carbon dioxide emissions reductions of 1.5 MtC of carbon dioxide for secondary steelmaking in 1994 which represents 6% of total US steelmaking energy use and 4% of total carbon dioxide emissions. Fig. 6 ranks the secondary steelmaking measures in a conservation supply curve. Some of the main cost-effective measures for secondary steelmaking include improved process control in the hot strip mill, recuperative burners in the rolling mill, improved process control in the EAF, and preventative maintenance. Table 6 provides a list of the measures ranked by their cost of conserved energy, internal rate of return, and simple payback periods.

Table 4
Energy savings, costs, and carbon dioxide emissions reductions for energy-efficiency technologies and measures applied to secondary steel production in the US in 1994

Option	Production (Mtonne)	Fuel savings (GJ/tonne crude steel)	Electricity savings (GJ/tonne crude steel)	Primary energy savings (GJ/tonne crude steel)	Annual operating costs (US$/tonne crude steel)	Retrofit capital cost (US$/tonne crude steel)	Carbon dioxide emissions reductions (kgC/t)	Share of production measure applied (percent)
Steelmaking electric arc furnace								
Improved process control (neural network)	35.9	0.00	0.11	0.33	−1.00	0.95	4.81	90%
Flue gas monitoring and control	35.9	0.00	0.05	0.17	0.00	2.00	2.40	50%
Transformer efficiency — UHP transformers	35.9	0.00	0.06	0.19	0.00	2.75	2.72	40%
Bottom stirring/stirring gas injection	35.9	0.00	0.07	0.22	−2.00	0.60	3.20	11%
Foamy slag practice	35.9	0.00	0.07	0.20	−1.80	10.00	2.88	35%
Oxy-fuel burners	35.9	0.00	0.14	0.44	−4.00	4.80	6.41	25%
Eccentric Bottom Tapping (EBT) on existing furnace	35.9	0.00	0.05	0.17	0.00	3.20	2.40	52%
DC-Arc furnace	35.9	0.00	0.32	1.00	−2.50	3.90	11.42	5%
Scrap preheating — Tunnel furnace (CONSTEEL)	35.9	0.00	0.22	0.66	−1.90	5.00	9.61	20%
Scrap preheating, post combustion — shaft furnace (FUCHS)	35.9	−0.70	0.43	0.63	−4.00	6.00	9.62	20%
Twin Shell DC w/scrap preheating	35.9	0.00	0.07	0.21	−1.10	6.00	3.04	10%
Secondary Casting								
Efficient ladle preheating	32.1	0.02	0.00	0.02	0.00	0.05	0.27	100%
Thin slab casting	32.1	2.86	0.57	4.62	−31.33	134.29	64.68	20%

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Table 4 (*continued*)

Option	Production (Mtonne)	Fuel savings (GJ/tonne crude steel)	Electricity savings (GJ/tonne crude steel)	Primary energy savings (GJ/tonne crude steel)	Annual operating costs (US$/tonne crude steel)	Retrofit capital cost (US$/tonne crude steel)	Carbon dioxide emissions reductions (kgC/t)	Share of production measure applied (percent)
Secondary Hot Rolling								
Process control in hot strip mill	31.3	0.26	0.00	0.26	0.00	0.61	3.59	88%
Recuperative burners	31.3	0.61	0.00	0.61	0.00	2.18	8.38	88%
Insulation of furnaces	31.3	0.14	0.00	0.14	0.00	8.73	1.92	30%
Controlling oxygen levels and VSDs on combustion air fans	31.3	0.29	0.00	0.29	0.00	0.44	3.95	50%
Energy-efficient drives in the rolling mill	31.3	0.00	0.01	0.03	0.00	0.17	0.39	50%
Waste heat recovery from cooling water	31.3	0.03	0.00	0.03	0.06	0.70	0.46	88%
General Technologies								
Preventative maintenance	35.9	0.09	0.05	0.24	0.02	0.01	4.09	100%
Energy monitoring and management system	35.9	0.02	0.01	0.06	0.00	0.15	1.02	100%

7.3. Energy conservation supply curve for US steelmaking (blast furnaces and steel mills)

Adding the integrated and secondary steelmaking cost-effective potentials, we identified energy savings of 18% and carbon dioxide emissions reductions of 19% for U.S. iron and steelmaking. Fig. 7 provides a summary supply curve for both integrated and secondary steelmaking combined. The savings in energy intensity are added using weighted intensity values, weighted by either the share of integrated or secondary steelmaking, depending upon which of these process can be made more efficient using the particular measure. Table 7 provides summary information on total cost-effective energy savings and carbon dioxide emissions reductions for the US iron and steelmaking sector in 1994.

8. Discussion and conclusions

Reviewing the industry as a whole (SIC 331 and SIC 332), we found that US steel plants are relatively old and production has fluctuated dramatically in the recent past. Metallurgical coal is

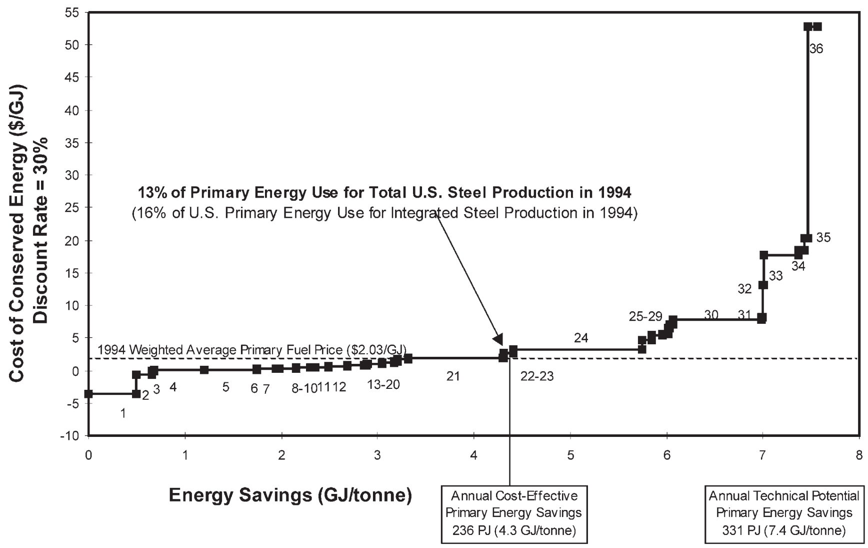

Fig. 5. Energy conservation supply curve for integrated steelmaking in the US. The horizontal axis depicts the cumulative primary savings on the specific energy consumption, expressed as GJ/tonne crude steel. The vertical axis depicts the annualized cost of conserved energy, expressed as \$(1994)/GJ-primary energy saved.

still the primary fuel for the sector but gas and electricity use has been increasing. Between 1958 and 1994, physical energy intensity for iron and steelmaking (SIC 331, 332) dropped 27%, from 35.6 GJ/t to 25.9 GJ/t, while carbon dioxide intensity (carbon dioxide emissions per tonne of steel) dropped 27% from 0.88 tC/t to 0.50 tC/t.

In a detailed analysis of US blast furnaces and steel mills (SIC 3312 only), we examined 47 specific energy efficiency technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of these measures. Based on this information, we constructed a conservation supply curve for US iron and steelmaking that found a total cost-effective reduction of 3.8 GJ/t, equivalent to an achievable energy savings of 18% of 1994 US iron and steel energy use and 19% of 1994 US iron and steel carbon dioxide emissions. We believe that this estimate is conservative since we may not have included all possible efficiency measures, and costs that were reported in the trade literature or demonstration project may be different than average or typical costs for these particular measures. A quantitative estimate of non-energy benefits, or production cost reduction, due to the energy efficiency measure is important for the economic analysis. However, we have not been able to fully quantify all economic benefits, leading to underestimation of the cost-effective potential. On the other hand, specific circumstances may increase the implementation costs, and hence affect the cost-effective potential negatively.

In the analysis of the economic potential for energy efficiency improvement we have used a discount rate of 30% to simulate investment criteria used by industry. To assess the cost-effective potential from a society perspective, commonly lower discount rates are used, e.g. 6–10%. Using such discount rates would increase the cost-effective potential to approximately 20%. On the other hand, industries also use much higher hurdle rates for small investment projects, resulting in discount rates of e.g. 50–100%. This would reduce the economic potential to 11% (discount rate

Table 5
Cost of conserved energy for selected measures in integrated steelmaking

	Integrated steelmaking efficiency measure	Primary CCE ($/GJ)	Primary energy savings (GJ/tonne)	Cumulative primary energy savings (GJ/tonne)	Internal rate of return (%)	Simple payback time (Years)
1	Adopt continuous casting	−3.52	0.50	0.5	53%	1.9
2	Injection of natural gas to 140 kg/thm	−0.55	0.16	0.66	76%	1.3
3	Increasing bed depth	0.00	0.02	0.68	>500%	0.0
4	Preventative maintenance	0.04	0.52	1.20	>500%	0.0
5	Pulverized coal injection to 130 kg/thm	0.14	0.55	1.75	51%	2.0
6	Hot blast stove automation	0.33	0.20	1.94	248%	0.4
7	Use of waste fuel in the sinter plant	0.35	0.03	1.97	186%	0.5
8	Improved blast furnace control systems	0.37	0.18	2.15	224%	0.4
9	Energy monitoring and management system	0.43	0.14	2.30	192%	0.5
10	Programmed heating — coke plant	0.44	0.05	2.35	149%	0.7
11	Controlling oxygen levels and VSDs on combustion air fans	0.46	0.14	2.49	133%	0.8
12	Automated monitoring and targeting system	0.68	0.19	2.68	120%	0.8
13	Process control in hot strip mill	0.75	0.18	2.86	86%	1.2
14	Reduction of air leakages — sintermaking	0.83	0.01	2.87	78%	1.3
15	Efficient ladle preheating	0.87	0.01	2.88	75%	1.3
16	Improved process control — sinter plant	0.94	0.01	2.89	69%	1.4
17	Pulverized coal injection to 225 kg/thm	1.00	0.15	3.05	41%	2.4
18	Recuperative burners	1.16	0.12	3.17	56%	1.8
19	Recovery of blast furnace gas	1.39	0.04	3.20	44%	2.3
20	Sinter plant heat recovery	1.82	0.12	3.32	34%	2.8
21	Thin slab casting	1.87	0.98	4.30	31%	3.3
22	Energy-efficient drives in the rolling mill	1.96	0.01	4.31	31%	3.2
23	Heat recovery on the annealing line	2.62	0.10	4.41	21%	4.0
24	Cogeneration	4.02	1.18	5.59	14%	6.1
25	Reduced steam use in the pickling line	4.77	0.09	5.67	6%	7.3
26	Hot charging	5.34	0.11	5.79	16%	5.9
27	Recuperator hot blast stove	5.66	0.07	5.86	3%	8.7

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Table 5 (*continued*)

	Integrated steelmaking efficiency measure	Primary CCE ($/GJ)	Primary energy savings (GJ/tonne)	Cumulative primary energy savings (GJ/tonne)	Internal rate of return (%)	Simple payback time (Years)
28	Variable speed drive on ventilation fan	6.49	0.01	5.87	0%	9.9
29	VSD: flue gas control, pumps, fans	6.98	0.03	5.90	−1%	10.7
30	BOF gas + sensible heat recovery	7.77	0.92	6.81	−3%	11.9
31	Waste heat recovery from cooling water	8.21	0.02	6.84	–	>50
32	Variable speed drive coke oven gas compressors	13.11	0.00	6.84	−12%	21.2
33	Coke dry quenching	17.78	0.37	7.21	−7%	35.7
34	Top pressure recovery turbines (wet type)	18.41	0.06	7.26	−9%	29.8
35	Insulation of furnaces	20.22	0.04	7.31	–	31.0
36	Coal moisture control	52.83	0.09	7.40	–	>50

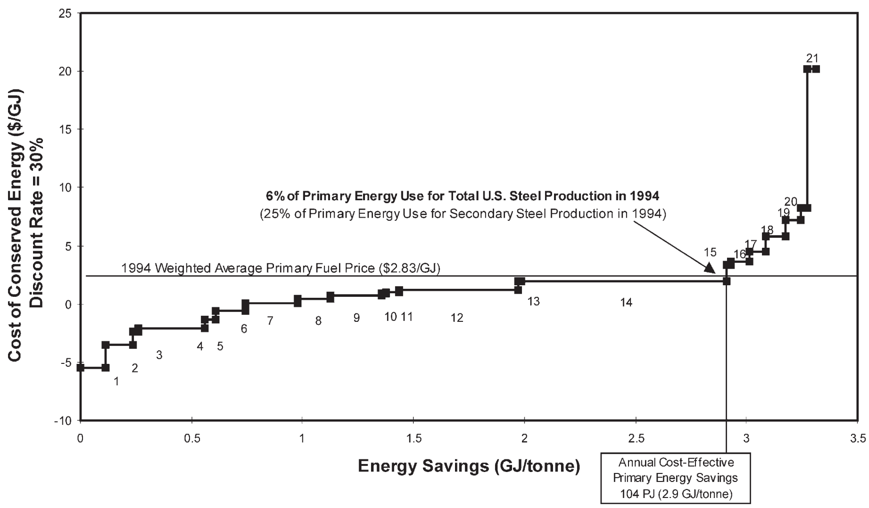

Fig. 6. Energy conservation supply curve for secondary steelmaking in the US. The horizontal axis depicts the cumulative primary savings on the specific energy consumption, expressed as GJ/tonne crude steel. The vertical axis depicts the annualized cost of conserved energy, expressed as $(1994)/GJ-primary energy saved.

Table 6
Cost of conserved energy for selected measures in secondary steelmaking

	Secondary steelmaking efficiency measure	Primary CCE ($/GJ)	Primary energy savings (GJ/tonne)	Cumulative primary energy savings (GJ/tonne)	Internal rate of return (%)	Simple payback time (Years)
1	Oxy-fuel burners	−5.52	0.11	0.11	109%	0.9
2	Scrap preheating, post combustion — Shaft furnace (FUCHS)	−3.49	0.13	0.24	96%	1.0
3	Bottom stirring/Stirring gas injection	−2.42	0.02	0.26	171%	0.2
4	Improved process control (neural network)	−2.08	0.30	0.56	204%	0.5
5	DC-Arc furnace	−1.33	0.05	0.61	136%	0.7
6	Scrap preheating — Tunnel furnace (CONSTEEL)	−0.60	0.13	0.74	76%	1.3
7	Preventative maintenance	0.10	0.24	0.98	>500%	0.0
8	Controlling oxygen levels and VSDs on combustion air fan	0.46	0.14	1.12	187%	0.5
9	Process control in hot strip mill	0.75	0.23	1.35	121%	0.8
10	Efficient ladle preheating	0.87	0.02	1.37	105%	0.9
11	Energy monitoring and management system	1.04	0.06	1.43	109%	0.9
12	Recuperative burners	1.16	0.54	1.97	79%	1.3
13	Energy-efficient drives in the rolling mill	1.96	0.01	1.98	44%	2.3
14	Near net shape casting/thin slab casting	1.98	0.92	2.91	33%	3.0
15	Twin Shell w/scrap preheating	3.33	0.02	2.93	28%	3.5
16	Flue gas monitoring and control	3.68	0.08	3.01	22%	4.3
17	Transformer efficiency — UHP transformers	4.47	0.08	3.09	18%	5.2
18	Eccentric bottom tapping (EBT) on existing furnace	5.81	0.09	3.17	14%	6.8
19	Foamy slag	7.19	0.07	3.24	8%	4.2
20	Waste heat recovery from cooling water	8.21	0.03	3.27	−4%	20.8
21	Insulation of furnaces	20.22	0.04	3.31	−12%	22.1

of 100%) to 13% (discount rate of 50%). The sensitivity of the results for the used discount rates is determined by the shape of the supply curve. Uncertainty in the data for each measure may also affect the shape of the curve, and hence the sensitivity for changes in the used discount rate.

Additional work is needed to improve the energy conservation supply curves and estimates of the cost-effective potential for energy efficiency improvement. The research needs concern the development of a detailed baseline by collecting more detailed energy consumption information

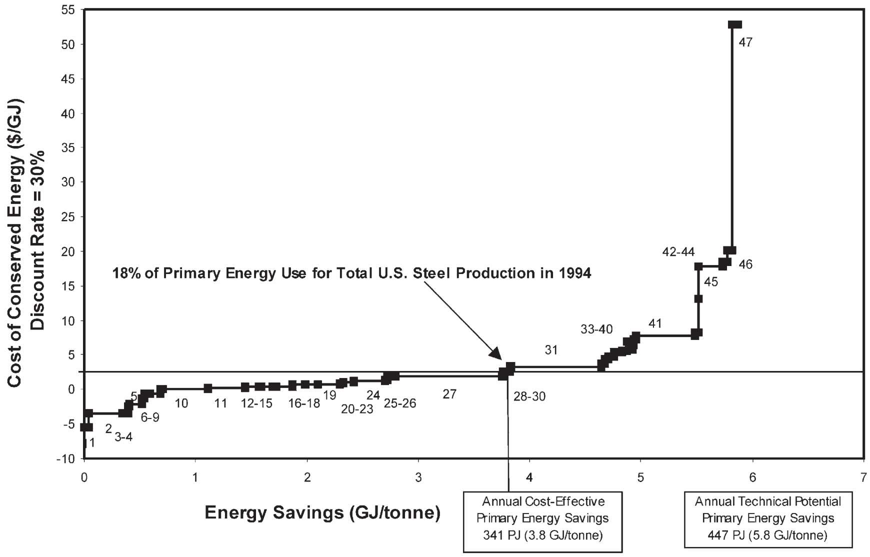

Fig. 7. Energy conservation supply curve for total US steel industry in 1994. The horizontal axis depicts the cumulative primary savings on the specific energy consumption, expressed as GJ/tonne crude steel. The vertical axis depicts the annualized cost of conserved energy, expressed as $(1994)/GJ-primary energy saved.

Table 7
Summary of cost-effective 1994 energy savings and carbon dioxide emission reductions

Steelmaking sector	Crude steel production (Mt)	Reduction in energy intensity (GJ/t)	Reduction in primary energy use[a] (PJ)	Share of total US iron and steel primary energy use (%)	Reduction in carbon dioxide emissions (MtC)	Share of total US iron and steel carbon dioxide emissions (%)
Integrated	55.4	4.3	236	13%	5.0	15%
Secondary	35.9	2.9	104	6%	1.5	4%
Total	91.2	3.8	341	18%	6.5	19%

[a] Primary energy is calculated using a conversion rate from final to primary electricity of 3.08, reflecting the difference between an average power plant heat rate of 10 500 Btu/kWh and a site rate of 3412 Btu/kWh, including transmission and distribution losses.

for the sector by process (especially for casting and rolling), as well as improving our understanding of the differences in statistical information on energy use in the steel industry. The characterization of individual measures can be improved by gaining additional information on investment and operations costs for the measures and through improved information on characterizing the existing technological disposition of the industry. Given the fact that the steel industry continues to evolve (for example 12 Mt of new EAF capacity has been added since 1994) additional updates of the analysis would need to reflect the changing industry.

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